A Multiple-objective Optimization Model of Transmission Enhancement Planning for Independent Transmission Company (ITC)

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Abstract: This paper proposes a multiple-objective fuzzy optimization model for Independent Transmission Company (ITC) to plan its transmission enhancements. There are several objectives to be considered, such as investment cost objective, power transferring efficiency objective, revenue objective, network congestion mitigating objective and environmental concern objective. The uncertain capital investment are also taken into account in the proposed model. By applying the fuzzy set theory, the above multi-objective optimization model has been converted into regular single-objective optimization problem to be solved. The numerical examples are given to demonstrate the effectiveness of the proposed model.

Keywords: Multiple-objective optimization, Transmission enhancement planning, Independent transmission company, Fuzzy set theory

I. INTRODUCTION

Transmission plays a key role in making the competitive electricity market work. It provides the means to broaden and strengthen competitive generation markets. A more robust transmission system would not only bring in competitive bidders from far away, but would also debalkanize market pockets in which dominant generators can exercise market power due to transmission restraints. However, transmission has not kept up with the growth in market, and some of the favored organizational fixes seem to do no more than ration existing assets [1], [2]. Creating the necessary transmission organizations and providing them with incentives to meet the demands placed on them is vital for the robust competition. The Independent transmission company (ITC) has offered a best structural form for transmission.

ITC is a commercial, profit-making transmission entity. It is independent from generation ownership and control. ITC owns and operates transmission assets, and it has rights to plan, finance and execute transmission expansions. ITC can benefits from increased efficiency or growth of market, and suffers commercial penalties for inadequate reliability or service. ITC has the ownership and operation together, and this efficient business structure encourages optimal decision-making. With the proper pricing framework and regulations, ITC can expand the network to carry more volume, and reduce congestion, and then offers an efficient, economical and reliable transmission for electricity market.

Although many approaches [3]-[5] have been proposed to plan the transmission networks in traditional vertically regulated power industry structure, it is still necessary to study how to plan the transmission expansion of ITC in the market environment.

This paper proposes a multiple-objective fuzzy optimization model for ITC to make its transmission enhance decisions. The maximization of network congestion mitigating objective, the maximization of power transferring efficiency objective, and the minimization of environmental impact objective are proposed to constraint ITC to offer good services to market customers and less environmental impacts. The minimization of capital investment, the maximization of revenue objective are considered for its own commercial success of ITC. The risk of capital raising of ITC is taken as constraint to be considered. By employing the fuzzy set theory[6]-[7], this multi-objective fuzzy optimization problem has been converted into regular single-objective optimization problem to be solved. The numerical examples are given to demonstrate the effectiveness of the proposed model.

II. INVESTMENT DECISION-MAKING

The goal of transmission enhancement planning is to determine to add or enhance what type of lines in which routes of power systems.

It is assumed that all possible enhanced or new-added routes, and all possible candidate line types in each route are given. The line types can be varied with line rated voltage, conductor size and type, tower configuration, and different parallel circuits.

Based on DC power flow models, the following multi-objective fuzzy optimization model is proposed to make expansion decisions.

1.Objective functions

(1). The first objective is to minimize the investment costs:

$$\text{Min } Z_1 = C(\mathbf{X}) \qquad (1)$$

where, $C(\mathbf{X}) = \sum_{i\in M}\sum_{j\in L_i} C_{ij}X_{ij}$ represents the investment cost of expansion plan. $\mathbf{X}$ stands for the set of investment decisions. C_{ij} is the investment cost of candidate line type j in route i. X_{ij} is 0-1 integer decision variables. M is the set of routes. L_i is the set of candidate line types in route i

(2). The second objective is to maximize the power transferring efficiency. The minimization of transmission loss is used to represent this objective:

$$\text{Min } Z_2 = D(\mathbf{X}) \tag{2}$$

where, $D(\mathbf{X})$ is the expected power loss of expansion plan. It is approximately expressed as the linear function of investment decisions $\mathbf{X}$ as follows:

$$D(\mathbf{X}) = D_0 + \sum_{i\in M}\frac{\partial D}{\partial \overline{P}_i}\left(\sum_{j\in L_i}\overline{P}_{ij}X_{ij} - \overline{P}_i\right) + \sum_{i\in M}\frac{\partial D}{\partial B_i}\left(\sum_{j\in L_i}B_{ij}X_{ij} - B_i\right) \tag{3}$$

where, D_0 is the expected power loss of existing network, $\frac{\partial D}{\partial \overline{P}_i}$ and $\frac{\partial D}{\partial B_i}$ are the sensitivity factors of power loss with respect to the active capacity $\overline{P}_i$ and susceptance B_i of route i in the existing network, $\overline{P}_{ij}$ and B_{ij} are the active capacity and susceptance of candidate line type j in route i.

(3). The third objective is to maximize mitigating the network congestion. It is expressed as the minimization of system expected demands not served(EDNS):

$$\text{Min } Z_3 = E(\mathbf{X}) \tag{4}$$

where, $E(\mathbf{X})$ is the system expected demand not served, and it is approximately expressed as the linear function of investment decisions $\mathbf{X}$:

$$E(\mathbf{X}) = E_0 + \sum_{i\in M}\frac{\partial E}{\partial \overline{P}_i}\left(\sum_{j\in L_i}\overline{P}_{ij}X_{ij} - \overline{P}_i\right) + \sum_{i\in M}\frac{\partial E}{\partial B_i}\left(\sum_{j\in L_i}B_{ij}X_{ij} - B_i\right) \tag{5}$$

where, E_0 is the EDNS index of existing network, $\frac{\partial E}{\partial \overline{P}_i}$ and $\frac{\partial E}{\partial B_i}$ are the sensitivity factors of EDNS with respect to the capacity and susceptance of route i in the existing network.

(4). The fourth objective is to minimize the environmental impacts. Since the right-of-way occupation is the main public concern of transmission, the minimization of line right-of-way occupied area is used to express this objective.

$$\text{Min } Z_4 = F(\mathbf{X}) \tag{6}$$

where, $F(\mathbf{X}) = \sum_{i\in M}\sum_{j\in L_i} F_{ij}X_{ij}$ is the new-added right-of-way occupied area of expansion plan, F_{ij} is new added right-of-way occupied areas of candidate line type j in route i.

(5). The fifth objective is to maximize the revenue from transmission. Because the transmission revenue is heavily relied on the volume of transmission, the objective is expressed as the maximization of load carrying capacity of network:

$$\text{Max } Z_5 = G(\mathbf{X}) \tag{7}$$

where, $G(\mathbf{X})$ represents the load carrying capacity of expansion plan, it is approximately expressed as the linear function of investment decisions:

$$G(\mathbf{X}) = G_0 + \sum_{i\in M}\frac{\partial G}{\partial \overline{P}_i}\left(\sum_{j\in L_i}\overline{P}_{ij}X_{ij} - \overline{P}_i\right) + \sum_{i\in M}\frac{\partial G}{\partial B_i}\left(\sum_{j\in L_i}B_{ij}X_{ij} - B_i\right) \tag{8}$$

where, G_0 is the load carrying capacity of existing network, $\frac{\partial G}{\partial \overline{P}_i}$ and $\frac{\partial G}{\partial B_i}$ are the sensitivity factors of load carrying capacity with respect to the capacity and susceptance of route i in the existing network.

2.The constraints

(1). Capital investment limits: The expansion decisions is determined by how much money ITC can raised. The financial risk is always existing. So, the following fuzzy constraint is used to express the uncertain of capital investment:

$$C(\mathbf{X}) \underset{\sim}{\leq} \hat{C} \tag{9}$$

where, $\hat{C}$ is the estimated maximum investment limit. "$\underset{\sim}{\leq}$" is a fuzzy unequal symbol, and it means "roughly less and equal than".

(2). The maximum acceptable power loss, $\overline{D}$, limits:

$$D(\mathbf{X}) \leq \overline{D} \tag{10}$$

(3). The maximum acceptable value of system expected demand not served, $\overline{E}$, limits:

$$E(\mathbf{X}) \leq \overline{E} \tag{11}$$

(4). The minimum acceptable value of new-added right-of-way occupied area, $\overline{F}$, limits:

$$F(\mathbf{X}) \le \overline{F} \tag{12}$$

(5). The minimum acceptable load carrying capacity, $\underline{G}$, limits:

$$G(\mathbf{X}) \ge \underline{G} \tag{13}$$

Besides above constrains, the investment decision variables are subject to the following constraints:

$$\sum_{j\in L_i} X_{ij} = 1 \qquad i \in M \tag{14}$$

$$X_{ij} = \{0,1\} \qquad j \in L_i,\ i \in M \tag{15}$$

III. OPERATION SIMULATION

In above model, $D(\mathbf{X})$, $E(\mathbf{X})$ and $G(\mathbf{X})$ are directly associated with system operation decisions. So, it is required to simulate the network configurations under various system operation states.

1. System state selection

System operation states are determined by the load levels, generation unit commitment and line states. The total number of system states for a practical system is so large that it is impossible to simulate all the system states. So, only the selected typical system states are used in this paper.

For load demands, several typical load levels are used to represent load variations.

For generation units, it is associated with load levels to be considered. For each typical load level, one generation unit commitment is given correspondingly. The generation outages are neglected.

For lines, both normal and outage states are considered, but the multiple outages is only considered up to 2 order.

2. System operation behavior simulation

For any system state t, the following double-objective optimization model is used to simulate the system operation behaviors:

$$\text{Min } W_1 = \sum_{i\in N} R_i \tag{16.a}$$

$$\text{Min } W_2 = \sum_{i\in M} r_i P_i^2 \tag{16.b}$$

$$\text{s.t. } \mathbf{P}_G + \mathbf{R} - \mathbf{B}\boldsymbol{\theta} = \mathbf{P}_D \tag{16.c}$$

$$|\mathbf{P}| \le \overline{\mathbf{P}} \tag{16.d}$$

$$\underline{\mathbf{P}_G} \le \mathbf{P}_G \le \overline{\mathbf{P}_G} \tag{16.e}$$

$$0 \le \mathbf{R} \le \mathbf{P}_D \tag{16.f}$$

where, N is the set of system buses, r_i and P_i are the resistance and active power of route i, $\mathbf{P}_D$ and $\mathbf{R}$ are the bus load demand vector and curtailment vector, $\mathbf{P}_G$, $\overline{\mathbf{P}_G}$ and $\underline{\mathbf{P}_G}$ are the bus generation vector and upper and lower capacity limit vectors, $\mathbf{B}$ and $\boldsymbol{\theta}$ are the bus susceptance matrix and voltage angle vector, $\overline{\mathbf{P}}$ is the route capacity limit vector.

The model is solved in two steps:

Step 1: Only objective W_1 is to be optimized under the constraints of Eqs. (16.c)~(16.f), then the minimal value of system demand not served, W_1^*, is obtained.

Step 2: Only objective W_2 is to be optimized under the constraints of Eqs. (16.c)~(16.f) and $W_1 \le W_1^*$, then the minimal power loss, W_2^*, is obtained.

W_1^* and W_2^* are the system demand not served E_t, and power loss D_t in system state t.

The sensitivity factors of E_t and D_t with respect to route i capacity and susceptance can be calculated as follows:

$$\partial E_t / \partial \overline{P}_i = \alpha_{\overline{P}_i} \tag{17}$$

$$\partial E_t / \partial B_i = (\alpha_{D_{i1}} - \alpha_{D_{i2}})(\theta_{i1} - \theta_{i2}) \tag{18}$$

$$\partial D_t / \partial \overline{P}_i = \beta_{\overline{P}_i} \tag{19}$$

$$\partial D_t / \partial B_i = (\beta_{D_{i1}} - \beta_{D_{i2}})(\theta_{i1} - \theta_{i2}) \tag{20}$$

where, $\alpha_{\overline{P}_i}$ and $\beta_{\overline{P}_i}$ are the dual variables of constraint i in Eqs. (16.d) with respect to objective W_1 and W_2 respectively. $\alpha_{D_{i1}}$ ($\alpha_{D_{i2}}$) and $\beta_{D_{i1}}$ ($\beta_{D_{i2}}$) are the dual variables of constraint i_1 (i_2) in Eqs. (16.c) with respect to objective W_1 and W_2 respectively. i_1 and i_2 are the terminal buses of route i.

3. System load carrying capacity simulation

For any system state t, the following optimization model is used to simulate the system load carrying capacity:

$$\text{Max } W_3 = \sum_{i \in N} P_{Si} \qquad (21.a)$$

$$\text{s.t. } \mathbf{P}_G - \mathbf{B\theta} = \mathbf{P}_S \qquad (21.b)$$

$$|\mathbf{P}| \le \overline{\mathbf{P}} \qquad (21.c)$$

$$\underline{\mathbf{P}_G} \le \mathbf{P}_G \le \overline{\mathbf{P}_G} \qquad (21.d)$$

$$P_{Si} \le \delta_i P_{S0} \quad i \in N \qquad (21.e)$$

where, P_{Si} is load demand that bus i can supply, $\delta_i = P_{Di} \Big/ \sum_{i \in N} P_{Di}$, P_{Di} is forecasted load demand of bus i. It is assumed that the proportion of every bus load to total system load is unchanged when loads is increasing. P_{S0} is the maximum load carrying capacity under normal system state. P_{S0} is obtained by solving the model (21), but Eqs. (21.e) is changed as an equal constraint.

The optimal objective of the above model, W_3^*, is G_t, the system load carrying capacity in state t. And, the sensitivity factors of G_t with respect to route i capacity and susceptance can be computed as follows:

$$\partial G_t \Big/ \partial \overline{P}_i = \gamma_{\overline{P}_i} \qquad (22)$$

$$\partial G_t \Big/ \partial B_i = (\gamma_{D_{i1}} - \gamma_{D_{i2}})(\theta_{i1} - \theta_{i2}) \qquad (23)$$

where, $\gamma_{\overline{P}_i}$ is the dual variable of constraint i in Eqs. (21.c), $\gamma_{D_{i1}}$ ($\gamma_{D_{i2}}$) is the dual variables of constraint i_1 (i_2) in Eqs. (21.b).

4. The sensitivity factor calculations

By applying above two models to all selected system states, we can obtain the required constants and sensitivity factors that used in the functions of $D(\mathbf{X})$, $E(\mathbf{X})$ and $G(\mathbf{X})$ as follows:

$$D_0 = \sum_{t \in T} p_t D_t \qquad (24)$$

$$\frac{\partial D}{\partial \overline{P}_i} = \sum_{t \in T} p_t \frac{\partial D_t}{\partial \overline{P}_i} \qquad (25)$$

$$\frac{\partial D}{\partial B_i} = \sum_{t \in T} p_t \frac{\partial D_t}{\partial B_i} \qquad (26)$$

$$E_0 = \sum_{t \in T} p_t E_t \qquad (27)$$

$$\frac{\partial E}{\partial \overline{P}_i} = \sum_{t \in T} p_t \frac{\partial E_t}{\partial \overline{P}_i} \qquad (28)$$

$$\frac{\partial E}{\partial B_i} = \sum_{t \in T} p_t \frac{\partial E_t}{\partial B_i} \qquad (29)$$

$$G_0 = \sum_{t \in T} p_t G_t \qquad (30)$$

$$\frac{\partial G}{\partial \overline{P}_i} = \sum_{t \in T} p_t \frac{\partial G_t}{\partial \overline{P}_i} \qquad (31)$$

$$\frac{\partial G}{\partial B_i} = \sum_{t \in T} p_t \frac{\partial G_t}{\partial B_i} \qquad (32)$$

where, T is the set of selected system states, p_t is the computed probability of state t. For system state t, its computed probability is:

$$p_t = \rho_t \frac{p_t'}{\sum_{t \in T} p_t'} \qquad (33)$$

$$p_t' = \prod_{l \in M_C} q_l \prod_{l \in M_L - M_C} (1 - q_l) \qquad (34)$$

where, q_l is the outage probability of line l. M_C is the set of outage lines in state t. M_L is the set of total lines. ρ_t is the occurrence probability of the load level of state t.

IV. SOLUTION ALGORITHM

The fuzzy set theory is employed to solve above-mentioned multi-objective fuzzy optimization problem.

First, we define fuzzy set $\widetilde{H}$ to express the satisfying degree of constraint (9). Its membership function is defined as follows:

$$\mu_{\widetilde{H}}(\mathbf{X}) = \begin{cases} 0 & C(\mathbf{X}) \ge \hat{C} + C_s \\ \dfrac{\hat{C} + C_s - C(\mathbf{X})}{C_s} & \hat{C} < C(\mathbf{X}) < \hat{C} + C_s \\ 1 & C(\mathbf{X}) \le \hat{C} \end{cases} \qquad (35)$$

where, the uncertain investment limit is varied within the range of $[\hat{C}, \hat{C} + C_s]$, C_s is the tolerance of investment limit. $\mu_{\widetilde{H}}(\mathbf{X})$ is the possibility of future capital investment to be raised.

Then, the fuzzy sets $\widetilde{C}$, $\widetilde{D}$, $\widetilde{E}$, $\widetilde{F}$ and $\widetilde{G}$ are introduced to express the realization degrees of objective (1), (2), (4), (6) and (7) respectively. The membership functions of these fuzzy sets are defined as follows:

$$\mu_{\widetilde{C}}(\mathbf{X}) = \begin{cases} 0 & C(\mathbf{X}) \ge \hat{C} + C_s \\ \dfrac{\hat{C} + C_s - C(\mathbf{X})}{\hat{C} + C_s - C^*} & C^* < C(\mathbf{X}) < \hat{C} + C_s \\ 1 & C(\mathbf{X}) \le C^* \end{cases} \qquad (36)$$

$$\mu_{\widetilde{D}}(\mathbf{X}) = \begin{cases} 0 & D(\mathbf{X}) \ge \overline{D} \\ \dfrac{\overline{D} - D(\mathbf{X})}{\overline{D} - D^*} & D^* < D(\mathbf{X}) < \overline{D} \\ 1 & D(\mathbf{X}) \le D^* \end{cases} \qquad (37)$$

$$\mu_{\widetilde{E}}(\mathbf{X}) = \begin{cases} 0 & E(\mathbf{X}) \ge \overline{E} \\ \dfrac{\overline{E} - E(\mathbf{X})}{\overline{E} - E^*} & E^* < E(\mathbf{X}) < \overline{E} \\ 1 & E(\mathbf{X}) \le E^* \end{cases} \qquad (37)$$

$$\mu_{\tilde{F}}(\mathbf{X})=\begin{cases}0 & F(\mathbf{X})\ge\overline{F}\\ \dfrac{\overline{F}-F(\mathbf{X})}{\overline{F}-F^{*}} & F^{*}<F(\mathbf{X})<\overline{F}\\ 1 & F(\mathbf{X})\le F^{*}\end{cases}\qquad(38)$$

$$\mu_{\tilde{G}}(\mathbf{X})=\begin{cases}0 & G(\mathbf{X})\le\underline{G}\\ \dfrac{G(\mathbf{X})-\underline{G}}{G^{*}-\underline{G}} & \underline{G}<G(\mathbf{X})<G^{*}\\ 1 & G(\mathbf{X})\le G^{*}\end{cases}\qquad(39)$$

where, C^{*},D^{*},E^{*},F^{*} and G^{*} are the optimal objective values of objective (1), (2), (4), (6) and (7) under the constraints of Eqs. (10)~(15) and $C(\mathbf{X})\le\hat{C}+C_s$.

Since the realization of objective (1), (2), (4), (6), (7) and satisfying of constraint (9) are contradictive each other, it is impossible to completely satisfy all these objective and constraint simultaneously. So, it is the only feasible way to make a compromise that has the maximum overall satisfying degree of all objectives and constraints.

Here, fuzzy set $\tilde{A}$ is used to express the overall satisfying degree of the realization of objective (1), (2), (4), (6), (7) and satisfying of the constraint (9), and its membership function is defined as follows:

$$\mu_{\tilde{A}}(\mathbf{X})=\min\left\{\mu_{\tilde{K}}(\mathbf{X})/\omega_{\tilde{K}},\tilde{K}\in\left[\tilde{C},\tilde{D},\tilde{E},\tilde{F},\tilde{G},\tilde{H}\right]\right.\qquad(40)$$

where, weight $\omega_{\tilde{K}}$ is introduced to express the relative importance of objective or constraint, and $\omega_{\tilde{K}}\ge 1$.

Hence, the proposed model described in Eqs. (1)~(15) is equivalently converted to maximize $\mu_{\tilde{A}}(\mathbf{X})$ subject to Eqs. (10)~(15), that is:

$$\begin{aligned}&\text{Max } \mu_{\tilde{A}}(\mathbf{X})=\lambda\\ &\text{s.t. } \mu_{\tilde{K}}(\mathbf{X})\ge\omega_{\tilde{K}}\lambda \quad \tilde{K}\in\left[\tilde{C},\tilde{D},\tilde{E},\tilde{F},\tilde{G},\tilde{H}\right]\\ &\quad 0\le\lambda\le 1\\ &\quad \text{Eqs. (10)~(15)}\end{aligned}\qquad(41)$$

Then, we can obtain the optimal solution as $X^{*}_{ij}(j\in L_i,\ i\in M)$ and λ^{*}. $X^{*}_{ij}(j\in L_i,\ i\in M)$ is the fuzzy optimal solution of network expansion, and λ^{*} is the overall satisfying degree of this expansion plan.

V. NUMERICAL EXAMPLES

A 28-bus system is used to demonstrate the validity of the proposed method.

Fig.1 depicts its network configurations. In Fig.1, the solid lines stand for existing routes, the dash lines are new-added routes, the data above the line is the route length(km). In route 12-24, 12-27 and 24-28, 500kV lines can be added or enhanced, the investment cost is 65000$/km, the line capacity is 1500MW. In route 7-27,12-23,21-22,21-23 and 23-24, Type A 220kV lines can be added, the investment is 36000$/km, and the line capacity is 300 MW. Except above-mentioned routes, all other routes can add Type B 220kV lines, the investment is 25000$/km, the line capacity is 200 MW. The total parallel circuits cannot excess 2 circuits per route in all routes, except route 4-24 and 4-5 can have 3 parallel circuits. The line outage rate of 500kV and 220kV lines are $\rho=0.0025L+0.126$ (1/yr) and $\rho=0.0034L+0.290$ (1/yr) respectively, L is the length of line in km, the repair duration of line outage is 16h. The widths of right-of-way occupied area are 48.27m for single 220kV line, 67.58m for single 500kV line, 68.27m for double 220kV line, 97.58m for double 500kV line, 88.27m for triple 220kV line, 117.58m for triple 500kV line. The following constants are used in the optimization process: $\hat{C}=\$35$ million, $C_s=\$35$ million, $\overline{D}=55.0$MW, $\overline{E}=3.57$MW, $\overline{F}=70$km^2, $\underline{G}=3410$MW.

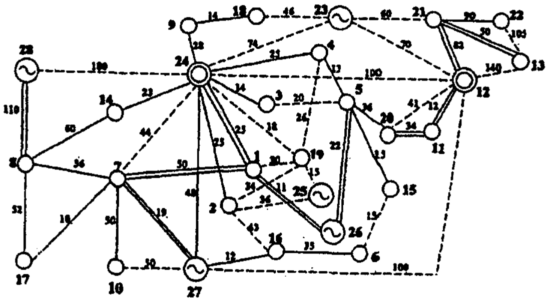

Fig.1. The 28-bus power system

There are 2 typical load levels to be considered, and the yearly equivalent duration of each level is 3500h. Table 1 gives the bus load demands of different load levels, and Table 2 lists the generation lower and upper limits for each load levels.

Table 1. Busload demands (MW)

Bus	Typical load states		Bus	Typical load states	
	I	II		I	II
1	210	190	12	270	240
2	140	130	13	360	320
3	150	130	14	90	80
4	170	150	15	150	140
5	210	190	16	110	100
6	200	180	17	100	100
7	220	200	18	100	90
8	170	160	19	100	90
9	190	170	20	80	80
10	220	200	21	180	180
11	150	140			

Table 2. Bus generation limits (MW)

Bus	Generation Limits (Load state I)		Generation Limits (Load state II)	
	Upper Limit	Lower Limit	Upper Limit	Lower Limit
23	600	180	600	180
25	400	120	200	60
26	400	120	200	60
27	1320	400	1020	300
28	2000	600	2000	400

Table 3 and Table 4 give the planning results of the system. Plan 1~5 are the optimization results of single objective (1), (2), (4), (6) and (7), and plan 6 is the optimization results of all objectives together. Table 3 lists some characteristic attributes of expansion plans. Table 4 lists the new-added lines of expansion plans.

From Table 3, we see that the overall satisfying degree of plan 1~5 is not good enough, although the satisfying degree of one particular objective is maximized. For plan 6, the satisfying degree of single objective is not the best, but the overall satisfying degree is the best. Plan 6 is the recommenced optimal expansion plan.

Table 3. Comparisons of different expansion plans

		Expansion plans					
		1	2	3	4	5	6
Investment Cost ($ million)		32.14	69.83	68.93	32.14	64.43	49.65
Power Loss (MW)		53.27	35.45	35.52	54.14	36.86	41.46
EDNS (MW)		3.47	0.0	0.0	3.55	0.1769	1.2081
Right-of-way occupied area (km^2)		38.61	69.06	68.34	37.19	64.72	47.83
Load carrying capacities (MW)		3487	4364	4366	3486	4369	3939
Objective realization degree	Objective C	1.0	0.0046	0.0284	1.0	0.1473	0.5374
	Objective D	0.0883	1.0	0.9965	0.0438	0.9279	0.6928
	Objective E	0.0290	1.0	1.0	0.0063	0.9504	0.6616
	Objective F	0.9569	0.0286	0.0505	1.0	0.1610	0.6757
	Objective G	0.0803	0.9948	0.9969	0.0792	1.0	0.5562
Future investment possible realization degree		1.0	0.0050	0.0307	1.0	0.1593	0.5813
Overall satisfaction degree		0.0290	0.0046	0.0284	0.0063	0.1473	0.5374

Table 4. The enhancement decisions of different expansion plans

Plan	Enhanced Routes			
	220 kV Lines		500kV Lines	
	Single Circuit	Double Circuit	Single Circuit	Double Circuit
1	10-27,12-13,12-23,16-27	4-19,19-25,21-23	12-27,24-28	
2	2-24,3-24,5-15,5-20,6-16,9-18,16-27, 21-22	2-25,4-5,4-19,4-24,6-15,10-27,12-13,12-23,13-22, 18-23,19-25,21-23	12-27	24-28
3	2-24,2-25,3-24,5-15,5-20,6-16,9-18, 16-27,21-22	4-5,4-19,4-24,6-15,10-27,12-13,12-23,13-22, 18-23,19-25,21-23	12-27	24-28
4	7-10,12-13,12-23,16-27	4-19,19-25,21-23	12-27, 24-28	
5	2-24,2-25,3-24,5-15,5-20,6-15,6-16, 13-22,16-27,18-23,21-22	4-5,4-19,4-24,10-27,12-13,12-23,19-25,21-23	12-27	24-28
6	2-24,3-24,5-15,6-16,9-18,10-27,12-13, 12-23, 16-27,21-22	4-19,19-25,21-23	12-27	24-28

VI. CONCLUSIONS

This paper proposes a multiple-objective fuzzy optimization model for ITC to make network expansion decisions.

The multiple objectives, such as investment cost objective, power transferring efficiency objective, revenue objective, network congestion mitigating objective and environmental concern objective, are considered simultaneously. The risk of capital raising is also taken into account as a fuzzy constraint.

By applying the fuzzy set theory, the proposed multi-objective optimization model has been converted into regular single-objective optimization problem to be solved.

The numerical examples have demonstrated the effectiveness of the proposed model.

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